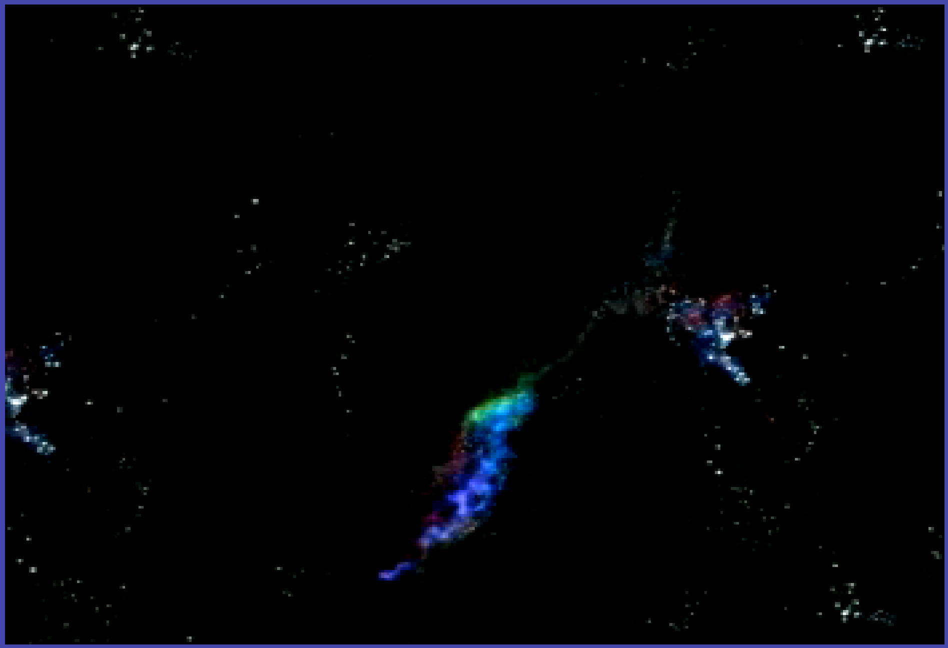
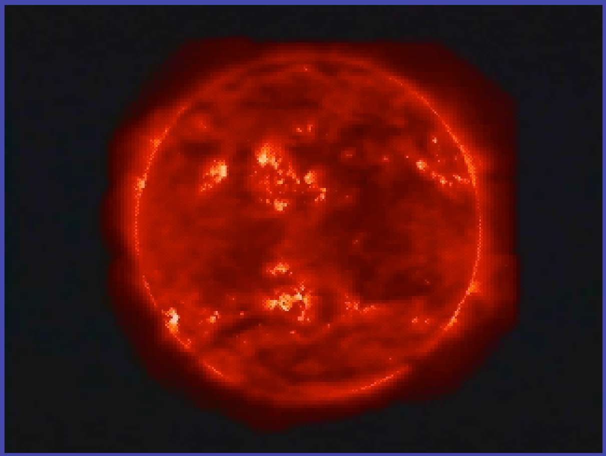
In the News...





An enormous explosion was seen on Dec 27 2004 by the Swift Gamma-ray telescope and by the Very Large Array radio telescopes. This was a tremendous flare from a magnetar. The same process occurs on the sun but at a much smaller scale.

Star Formation & Stellar Evolution

- Observations of Stellar Types
- Formation of Low and High Mass Stars
- Physical Processes
- New Results from Spitzer
- Nuclear Evolution and Nucleosynthesis
- Giants and Instabilities
- Ejections
- Massive Star Evolution
- Binary Star Evolution

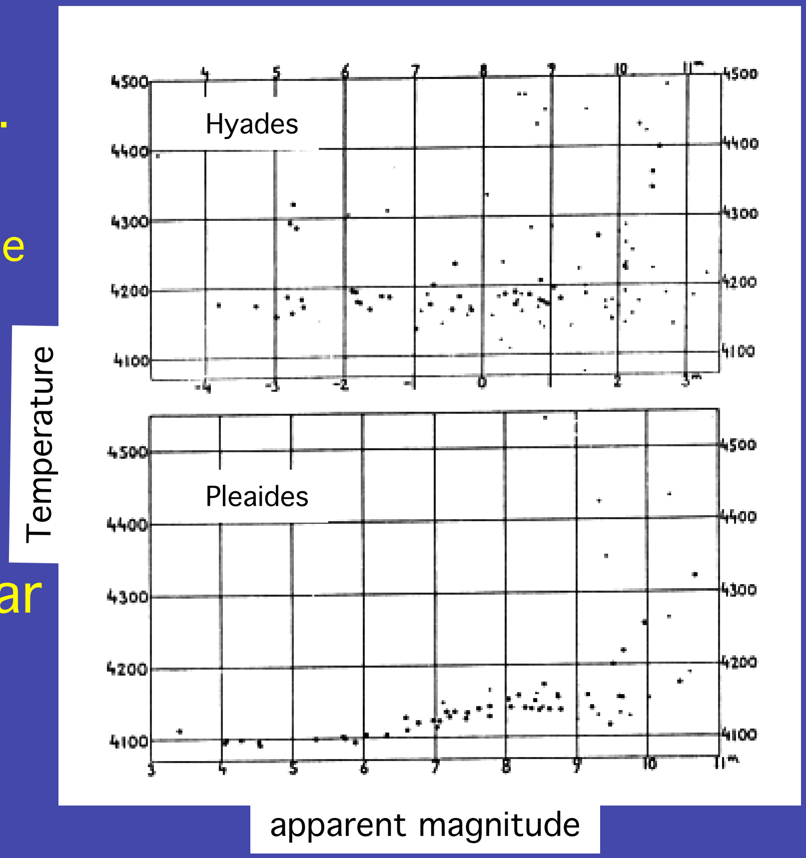
The HR diagram

Stars are classified by stellar brightness (better: luminosity) and stellar temperature (or color).

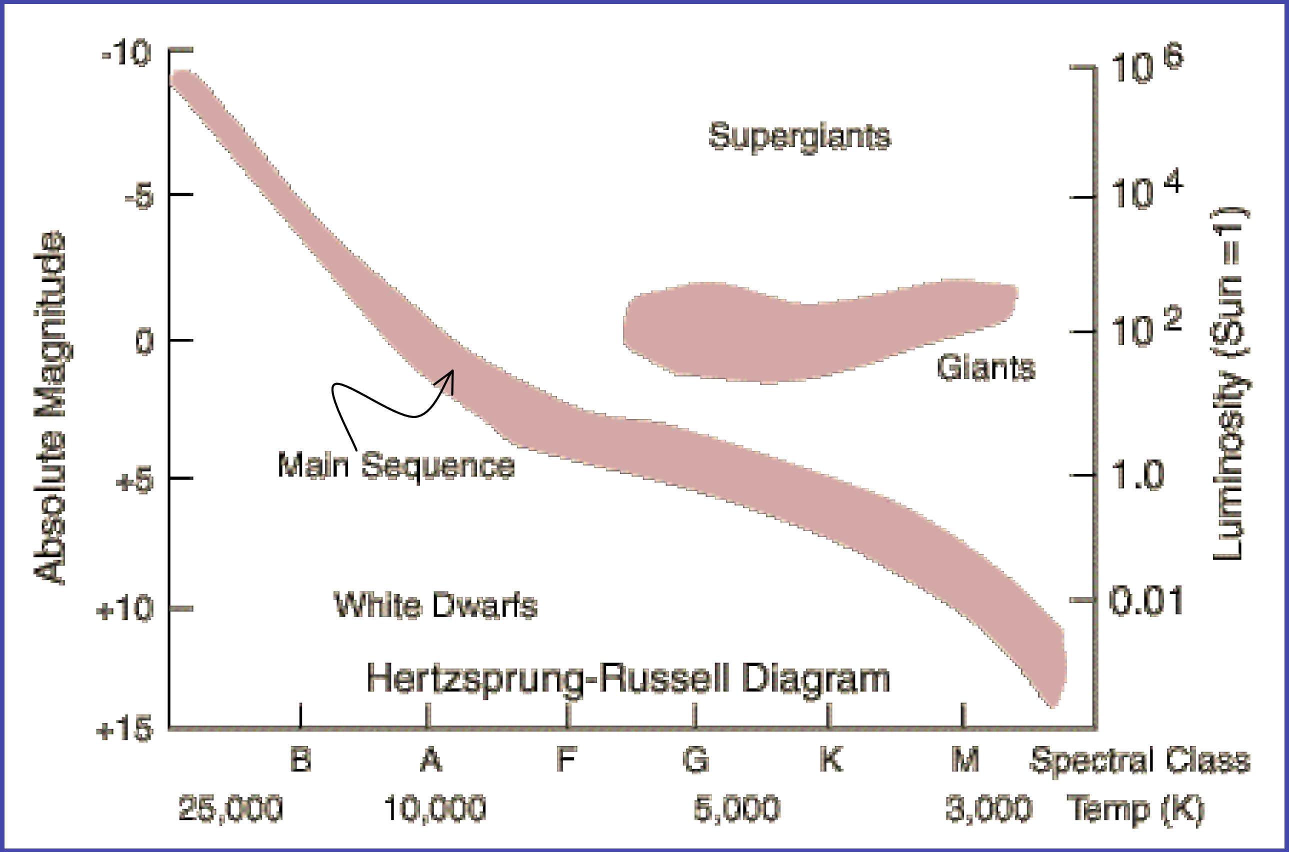
What's the distribution of stellar brightness vs. temperature like?

1911- Ejnar Hertzsprung & H.N. Russell plot the apparent brightness vs. temperature for the Pleiades and Hyades star clusters (advantage: relative apparent brightnesses ~ relative luminosities)

The HRD: a fundamental tool for stellar astrophysics



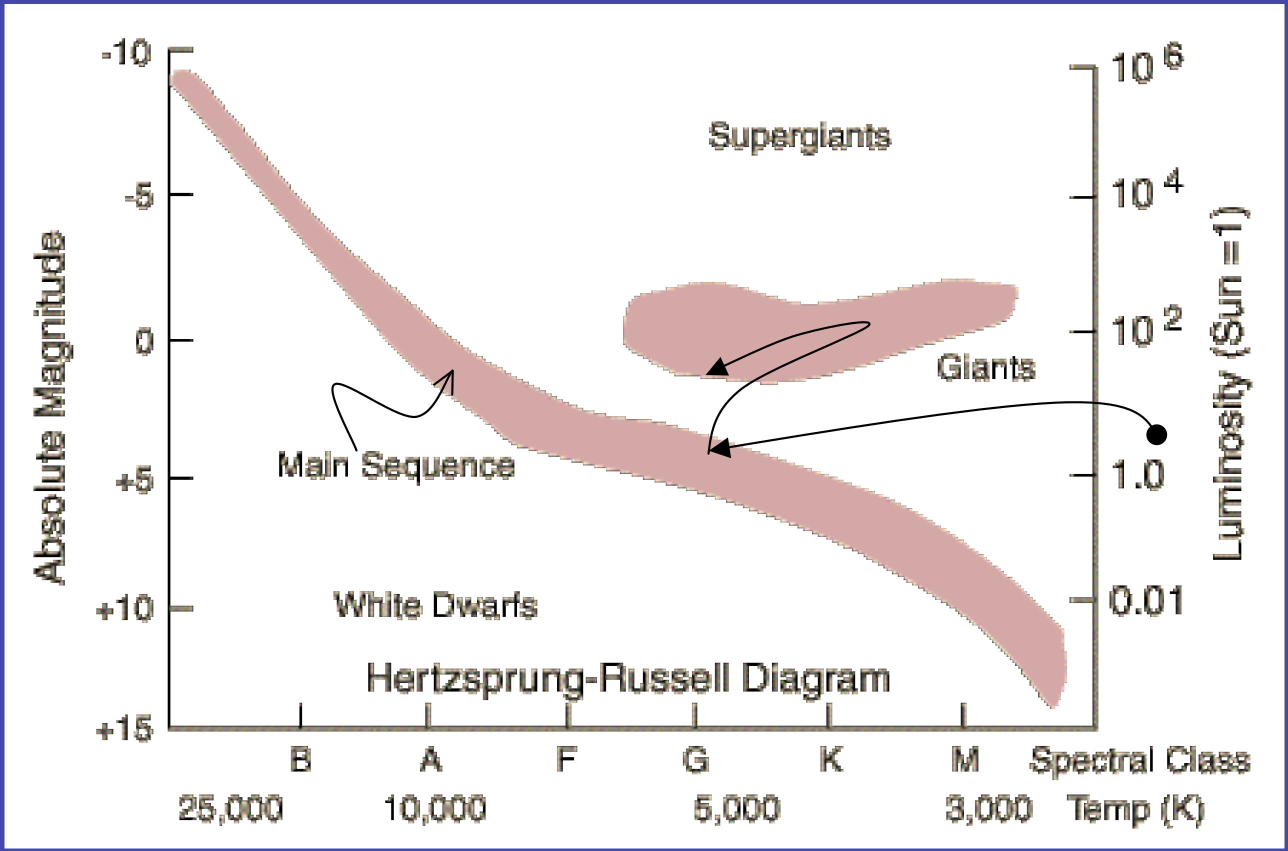
Regions of the HR diagram



~90% of known stars lie on the main sequence

Schematic HRD:
Temperature (X-axis, backward) vs. magnitude (numerically backward)

Movement in the HRD



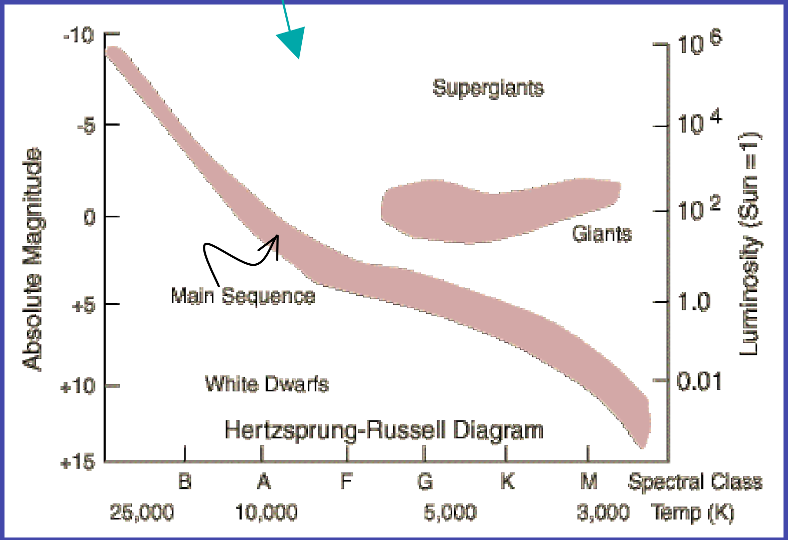
Location of a star in the HRD depends on the stars intrinsic properties (mass, age, composition...)

Stars are located at a particular spot on the Main Sequence. As they age they move off the MS.

Star Formation: General Problem

Star formation (and stellar evolution in general) describes how to go from this:

To This:



Star Formation: Sites

Stars are composed of ionized gas; they form out of clouds of gas located in galaxies.

Stars are held together by gravity: preferentially form in high dense IS clouds.

Forces on an IS cloud

- gravity
- thermal pressure force
- magnetic force
- centrifugal force

Interplay between these forces will determine if a star can form

Star Formation: Triggers

Cloud Collapse can be triggered by external impulsive events:

- stellar winds
- explosions
- cloud collisions
- galaxy-galaxy interactions
- etc

Cloud Collapse

In an ideal case (no rotation or magnetic field) the collapse of an IS cloud depends on the inward pull of gravity vs. the outward push of the internal pressure of the gas.

Jean's length

$$R_J = \sqrt{\frac{15kT}{4\pi G m_H \rho}}$$

Jean's Mass

$$M_J = 4\pi R_J^3 \rho$$

$$= \sqrt{\left(\frac{3}{4\pi\rho}\right)\left(\frac{5kT}{G m_H}\right)^3}$$

If $M > M_J$, gravity wins and cloud will collapse; collapse if $R < R_J$

Heating and Cooling

Cloud collapse driven by density inhomogeneities: region of greatest density attracts mass (regions of lower density act like a repulsion of mass)

As cloud collapses, thermal energy rises

recall Virial Theorem: Thermal Energy ~ $1/2\ G\ M^2/r$

Thermal energy can be radiated by electronic recombination+de-excitation to low energy photons which can escape, or via ro-vibrational excitation of H_2, CO and other molecules

Rotation

for any parcel of mass, for a torque-free system, angular momentum is conserved:

$$\overrightarrow{L} = \overrightarrow{r} \times \overrightarrow{p} = mr^2\omega = \text{constant}$$

as r decreases, ω must increase, and the centrifugal force increases.

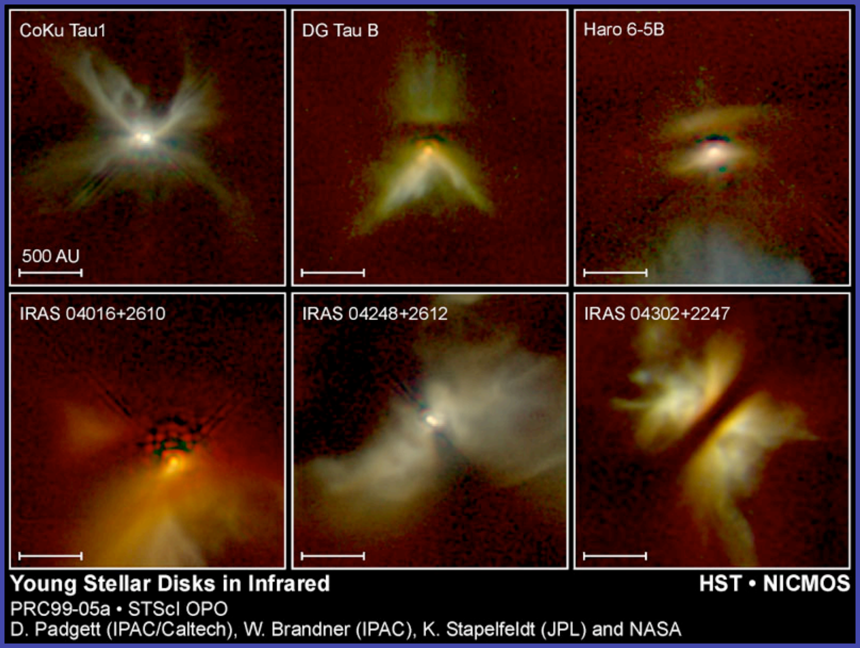
$$F_c = m\omega^2 r$$

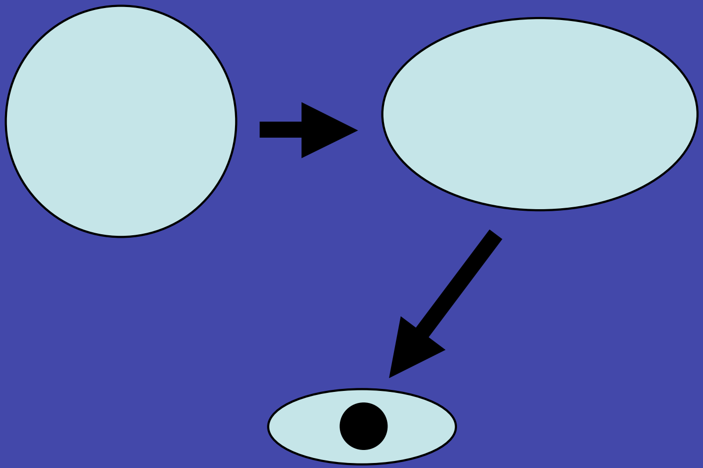
eventually the centrifugal force can halt the gravitational collapse, unless angular momentum can be removed or stored

Stellar Disks

A "quasi-spherical" collapse will eventually flatten due to the competition between gravity and the centrifugal force.

A large (many AU), massive disk can help store the angular momentum of the infalling material





Material feeds the star through the accretion disk

Disks are common (fundamental) to young stars

Magnetic Fields

in a collapsing, magnetized cloud, conservation of magnetic flux means that, if the field is frozen to the plasma (for sufficiently high ionizations) then the magnetic pressure generated can also oppose gravity and stop the infall.

But magnetic fields can also aid in accreting material:

- magnetic coupling between the protostar/protostellar disk and ambient cloud can remove angular momentum from the protostar
- ions will tend to drift outward along the magnetic field lines while neutrals are unaffected by the B field. This process is called ambi-polar diffusion, and can also remove angular momentum

Observing Star Formation

Free fall time for a gas cloud unsupported by internal pressure is

$$t_{ff} = \sqrt{\frac{3\pi}{32G\rho}} = 3.4 \times 10^7 n^{-0.5} \text{ years}$$

Typically, $n>50$ cm^{-3} thus $t_{ff}<5 \times 10^6$ years - slow process

but star formation is a dynamic process and we can observe (what we believe are) very young stars in various phases of formation

Protostellar Classes

Protostars are divided into 3 (4) classes based on the amount of IR radiation they produce (more IR=> younger)

- Class I: sources that are (believed to be) undergoing infall along with bipolar outflows
- Class II: Young stars with disks and winds (ex: T Tauri). Show lots of activity: chromospheric emission lines, flares, etc.
- Class III: all accretion activity has ~ stopped, no more accretion disk; star just about to start on the main sequence.
- and also Class 0: emission peaks at very long wavelengths (submm). Youngest stellar class, star just at start of infall stage?

X-ray Properties of Protostars

Young (low mass) stars usually show extreme stellar activity, dependent on age:

- fast rotation
- convective
- active dynamos
- also lots of gravitational energy
- lots of shock energy from outflows interacting with the ISM

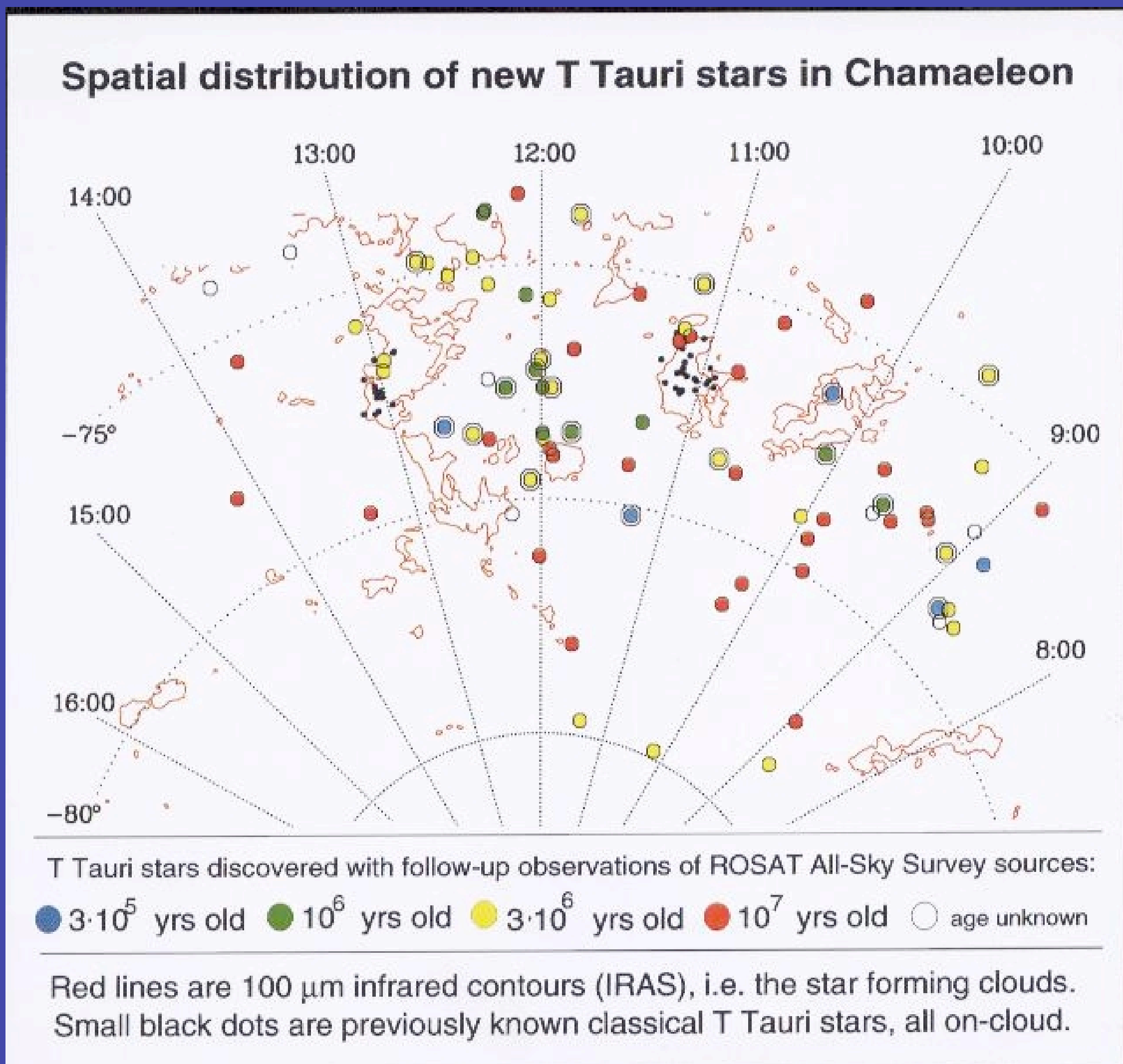
Low-mass Protostars are sites of X-ray emission from stellar flares, active corona, shock heated gas (non-thermal radiation?)

X-ray Observations of Young Stars

X-rays are useful probes of star formation:

- stellar activity generates large X-ray fluxes (as high as L_x/L_{bol} ~0.001)
- hard X-rays can penetrate dark clouds (typical $N_H \sim 10^{23}$)

T-Tauri Surprises



Red lines are 100 μm infrared contours (IRAS), i.e. the star forming clouds.
Small black dots are previously known classical T Tauri stars, all on-cloud.

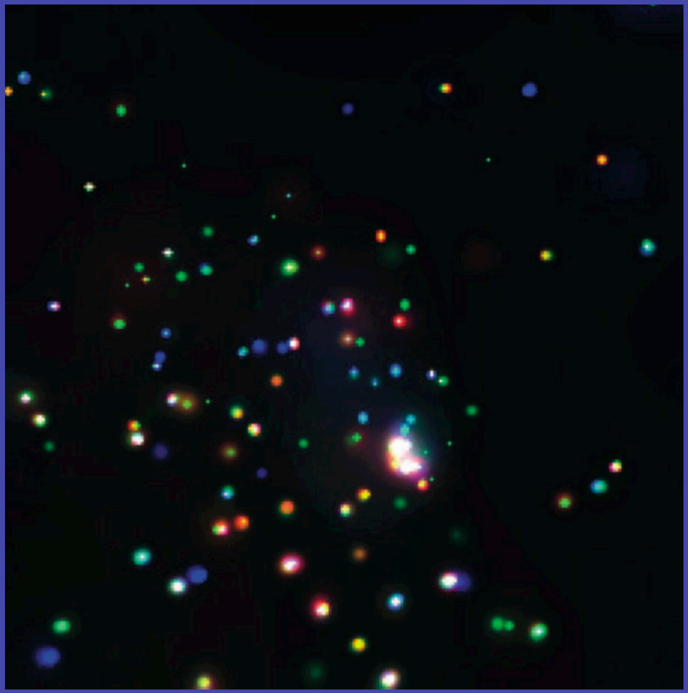
T-Tauri stars are young, low-mass stars (usually) with strong chromospheric activity

ROSAT finds a surprising number of very young stars outside molecular clouds:

- ejection?
- dissipation?

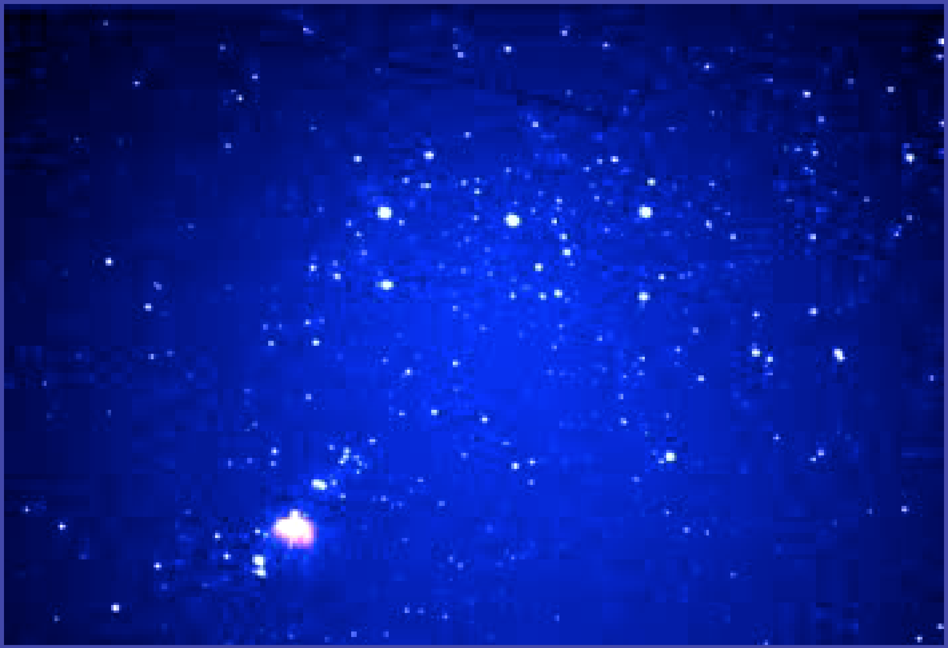
Young Star Colors

Chandra imageof the Trifid Nebula.
Color represents photon energy (red:low, blue:high)



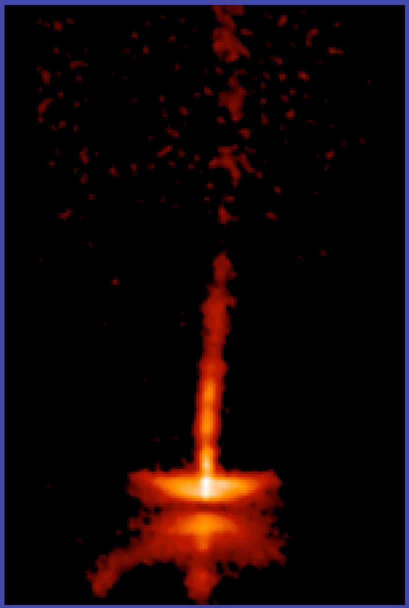
red sources are un-embedded; blue are either embedded or high energy sources (hotter; non-thermal?)

Proplyds

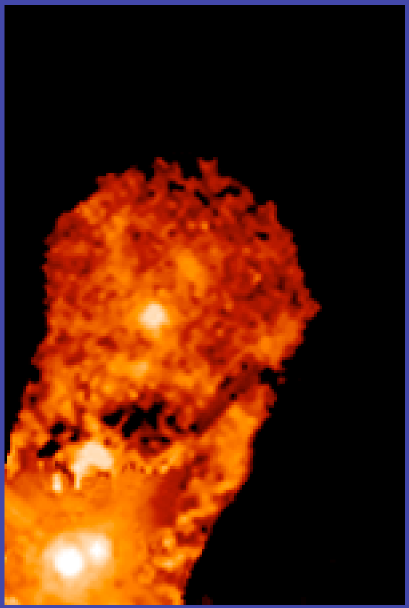


Proplyd= “protoplanetary disk”: solar system in formation?

Stellar Jets



HH30



XZ Tau

Collimated outflows (jets) emerge from the accretion disk. Physics of jet acceleration not certain, though it's not radiatively driven (not enough photons)

Some combination of gravitational energy release coupled with magnetized flow?

Companions

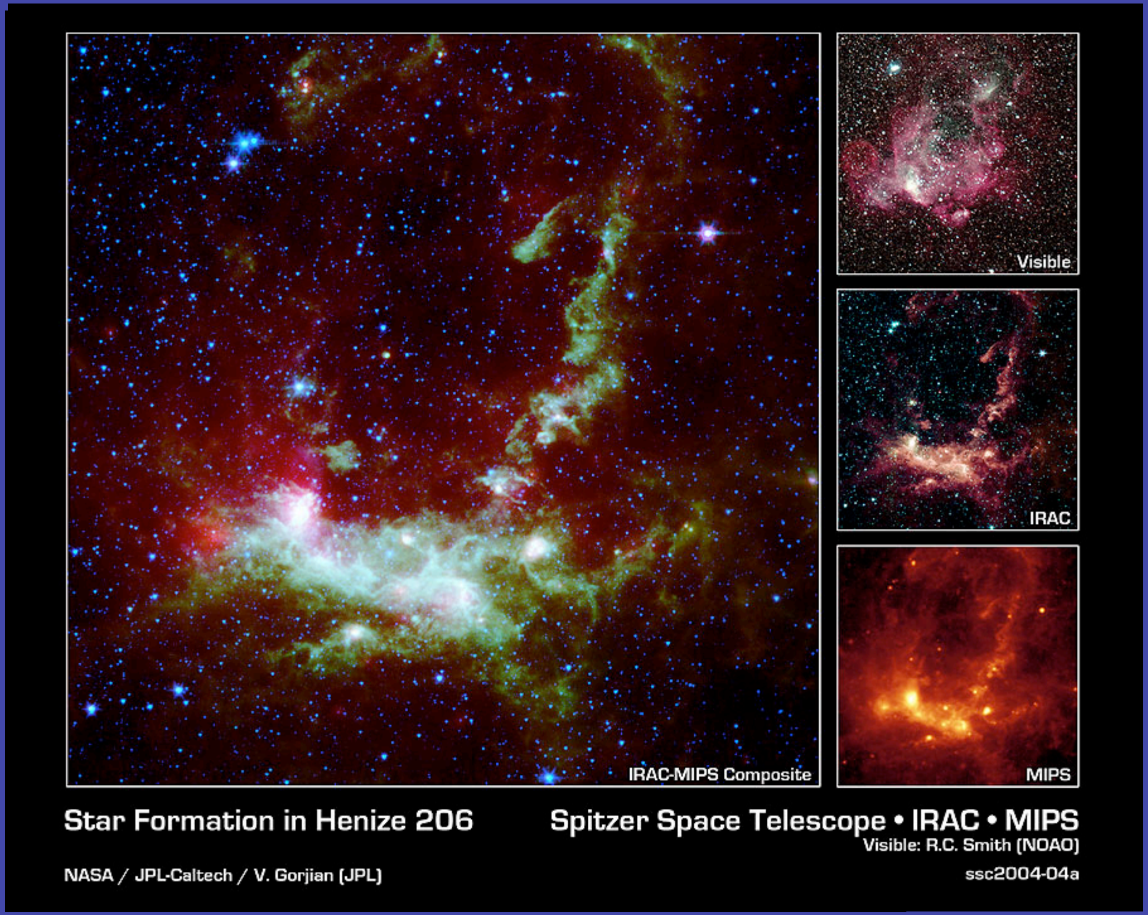
Disks around stars can:

- dissipate
- form solar systems
- form stellar companions

Binary systems (2 stars bound gravitationally, orbiting common center of mass) very common (~50% of stars are known binaries)

- binaries can also form via capture in clusters with high stellar densities

Spitzer Space Telescope & Triggered Star Formation



Spitzer is an IR satellite observatory (launched Aug 2003)

Hen 206 is an obscured star forming region in the LMC.

Spitzer reveals hidden population of young stars along the nebula.

Stellar Nuclear Evolution

After nuclear fusion (H-burning) begins in the protostellar core, the star is on the main sequence.

This occurs at a core temperature of about 15 million K or more.

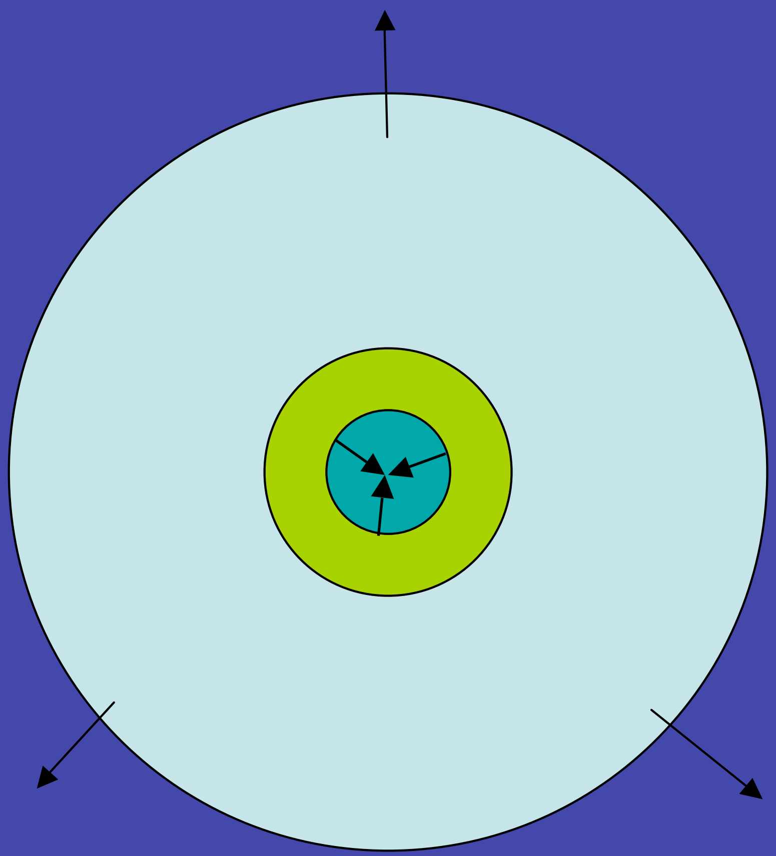
The Main sequence is the longest stage of a star's life: stable fusion, lots of H fuel.

Length of Main Sequence life depends on stellar mass:

$$\text{O-type star}(M \sim 30 M_\odot) : \tau_{MS} \sim 2.0 \times 10^{6} \text{ yrs}$$
$$\text{G-type star}(M \sim 1 M_\odot) : \tau_{MS} \sim 1.5 \times 10^{10} \text{ yrs}$$
$$\text{M-type star}(M \sim 0.5 M_\odot) : \tau_{MS} \sim 7.5 \times 10^{10} \text{ yrs}$$

Eventually the H fuel in the core will run out (nearly completely converted to He.)

H Exhaustion & H-shell burning



He core can no longer support itself so it contracts

Contraction raises T in H-burning shell

H-burning shell produces more energy

Envelope Expands

Inert He core
H-burning shell
H envelope

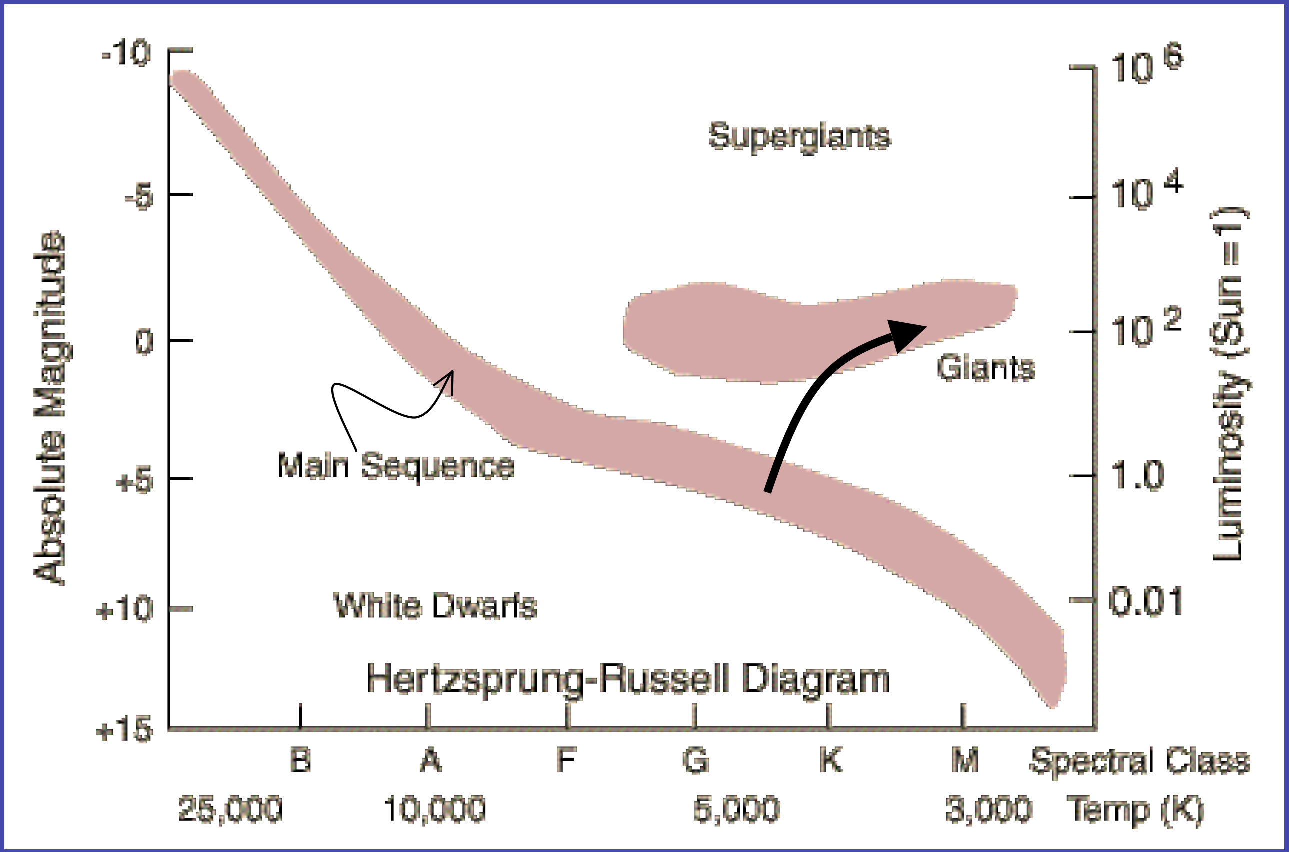
H shell Burning & the Giant Branch

Radius of the star increases; photospheric temperature decreases

Star moves to the right (cooler) and upward in the HRD

Star becomes a red giant

Red Giant Branch



White Dwarfs

As core continues to contract, it heats up. Core temperature determined by mass of overlying layers.

He fusion requires core temperatures of 10^8 K

For low mass stars (M~1Msun) central temperature won't get high enough for He fusion to take place

core eventually becomes supported by the pressure of electrons, which, as density increases, achieve higher and higher energy states due to the Pauli Exclusion Principle.

This quantum-mechanical pressure is called electron-degeneracy pressure

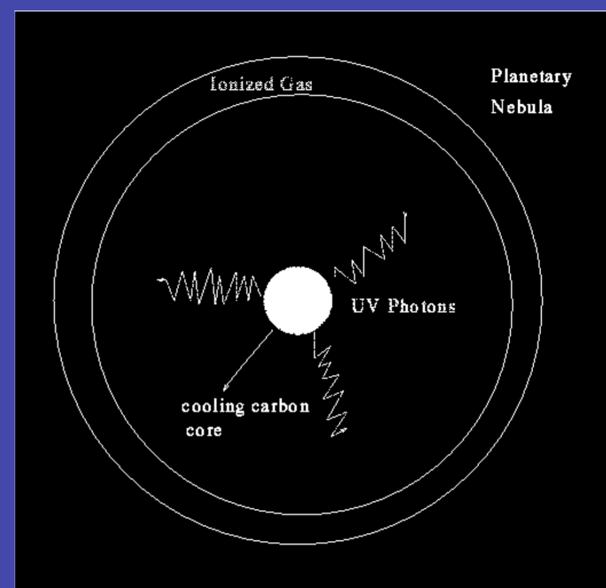
$$P = \left(\frac{\pi^2 \hbar^2}{5 m_e m_H^{5/3}}\right)\left(\frac{3}{\pi}\right)^{2/3}\left(\frac{N_H \rho}{N_e}\right)^{5/3}$$

P independent of T

Planetary Nebulae

Cat's Eye Nebula: spherical older ejections, complicated inner morphology

Outer envelope of star can eventually be driven away from the core/shell, forming a "planetary nebula"



Helium Burning

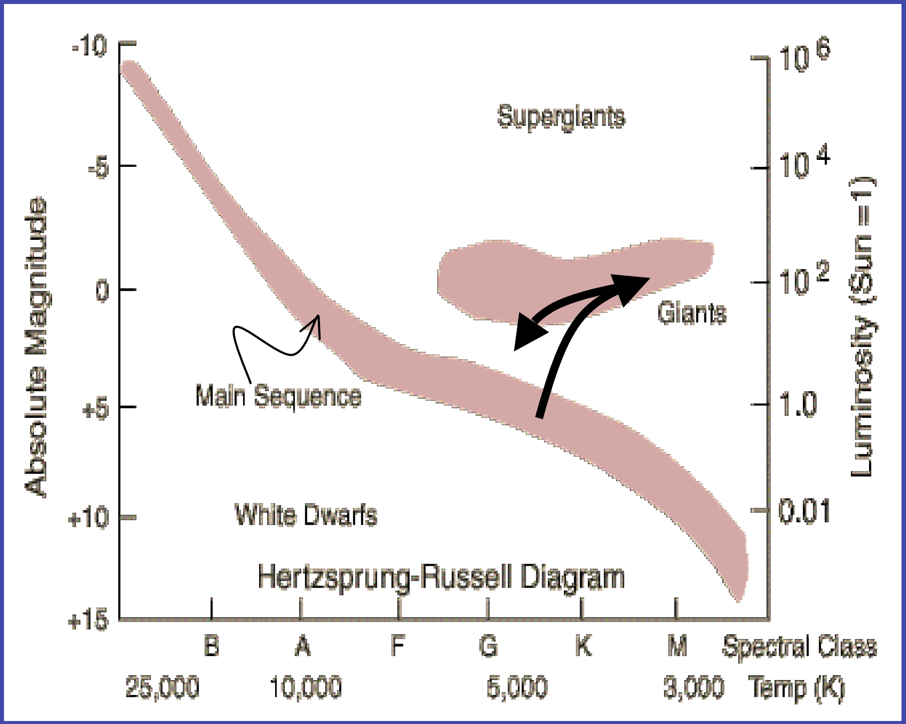
For more massive stars (≥1 Msun) the central temperature can reach 10^8 K so that He can fuse. This is called the triple-alpha process: 3 He nuclei (alpha particles) combine to one C nucleus.

If this occurs under degenerate conditions, explosive nucleosynthesis: He Flash

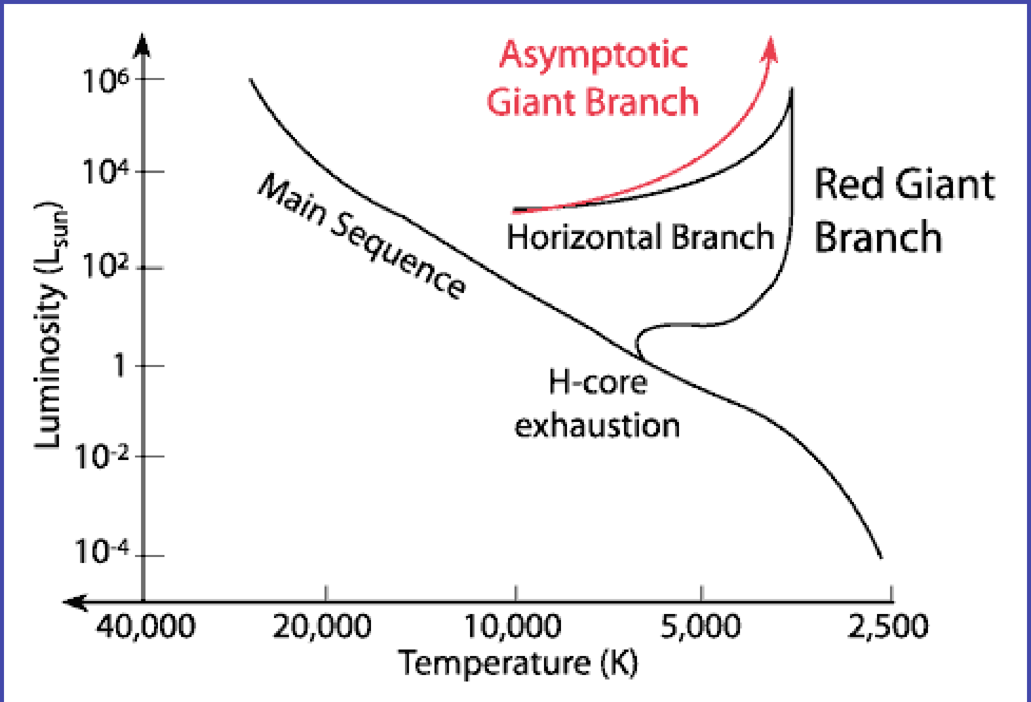
The core expands and lowers the T of the H-burning shell, which is providing most of the pressure support: star contracts and heats up.

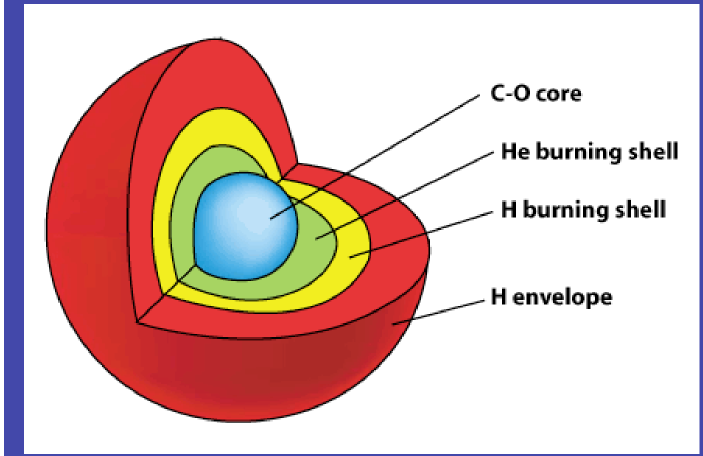
“He-Main Sequence” lasts far shorter than H-Main Sequence

Either: WD+PN or further evolution



Asymptotic Giant Branch





H & He-burning shells power rapid expansion; star can start to pulsate, driving a stellar wind from the photosphere. Dust and molecules can form and be dispersed. Wind might be shaped by presence of a companion or a magnetic field.

Formation of Massive Stars

Formation of massive stars similar to that of low mass stars with one important difference

Massive stars (M>8 Msuns) have large radiation fields which provide for significant radiation pressure.

$$P_{rad} = \frac{4}{3c}\sigma T^4$$

Radiation pressure is sufficient to halt infall

Formation Scenarios

2 scenarios of massive star formation:

- somehow the infalling material is shielded from the radiative flux from the protostar: thick disk?
- perhaps massive stars form by a process of hierarchical accretion

OB Associations

Observationally, massive OB stars only form in groups called "clusters" (gravitationally stable) or "OB associations" (short lived groups which will evaporate).

- Need high stellar densities to form?
- Need very high gas densities to form?

Nuclear Evolution

Star with M>8Msun can achieve core temperatures which are high enough to fuse C (about 6×10^8 K)

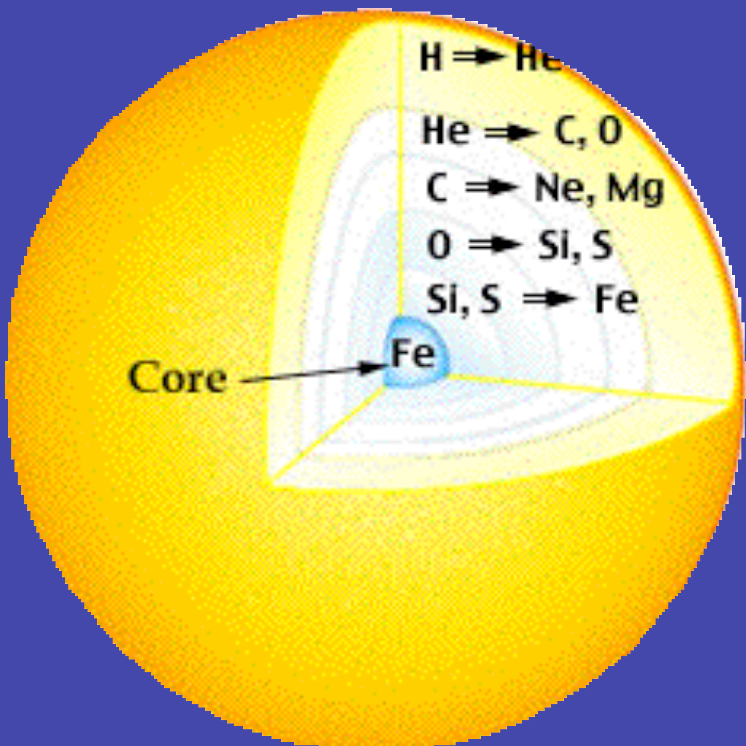
Nuclear burning stages: Log(duration/yr) for a 75 $M_{\odot}$ star

Mass	H	He	C	Ne	O	Si
75$M_{\odot}$	6.5	5.7	3.0	-0.2	-0.1	-2.2

From Woosley & Heger 2002

2 days!

Nucleosynthesis past C



nuclear burning in shells gradually results in formation of heavier nuclei (Ne, Mg, O, Si, S)

After Si burns to Fe, stellar core no longer has a means of pressure support: fusion or fission of Fe robs core of energy

Core collapse

End States

Subsequent evolution after the formation of the Fe core extremely rapid (seconds)

Outer envelope ejected as a supernova explosion (supernova remnant)

core either:

- is completely destroyed
- becomes a neutron star
- or becomes a black hole

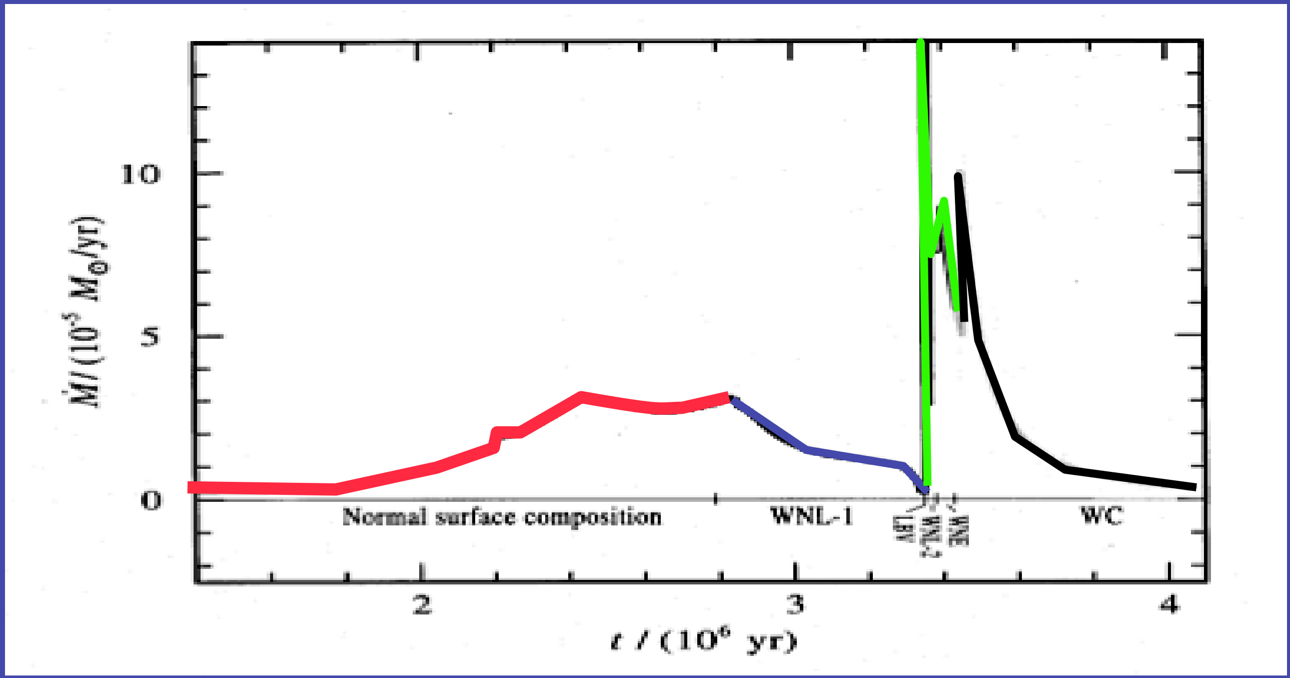
Instabilities

Intermediate and massive stars are subject to atmospheric instabilities.

Typically such pulsations are driven by opacity changes in the stellar atmosphere: star contracts, opacity builds up, excess pressure expands the star, star gets fainter and cooler, opacity decreases, less pressure, star contracts.

Particularly important are the Cepheid Variables: radial pulsators whos pulsational period is proportional to the luminosity of the star

Mass-Loss History



From Langer et al. 1994

	M	log(t/yr)	M_{lost}	M_{end}
MS	60.0	6.5	17.6	42.4
WN	42.4	5.8	21.7	20.7
LBV	20.7	4.9	5.4	15.3
WNE/WC	15.3	5.8	11.4	3.9

The surface of the star evolves as well. As the atmosphere becomes contaminated with heavier elements (N, C, O) radiative driving becomes more efficient. Star can lose most of it's mass via its stellar wind.

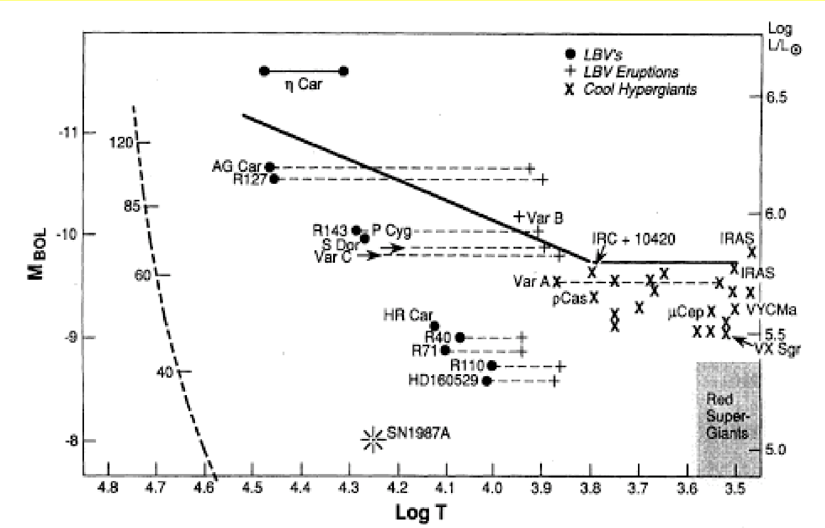
Wolf-Rayet Stars

Very massive stars will evolve to “Wolf-Rayet” stars, characterized by strong emission lines produced by an optically thick stellar wind.

During this phase the mass loss rate increases by about a factor of 10.

Only a few hundred WR stars are known

Luminous Blue Variables



Humphrey and Davidson 1994

Humphreys-Davidson limit: In the upper HRD, there's a boundary beyond which stars don't exist in a stable configuration.

Stars near this limit are also near the Eddington Limit (where radiation pressure on electrons exceeds gravity)

Stars near this limit are sometimes called Luminous Blue Variables

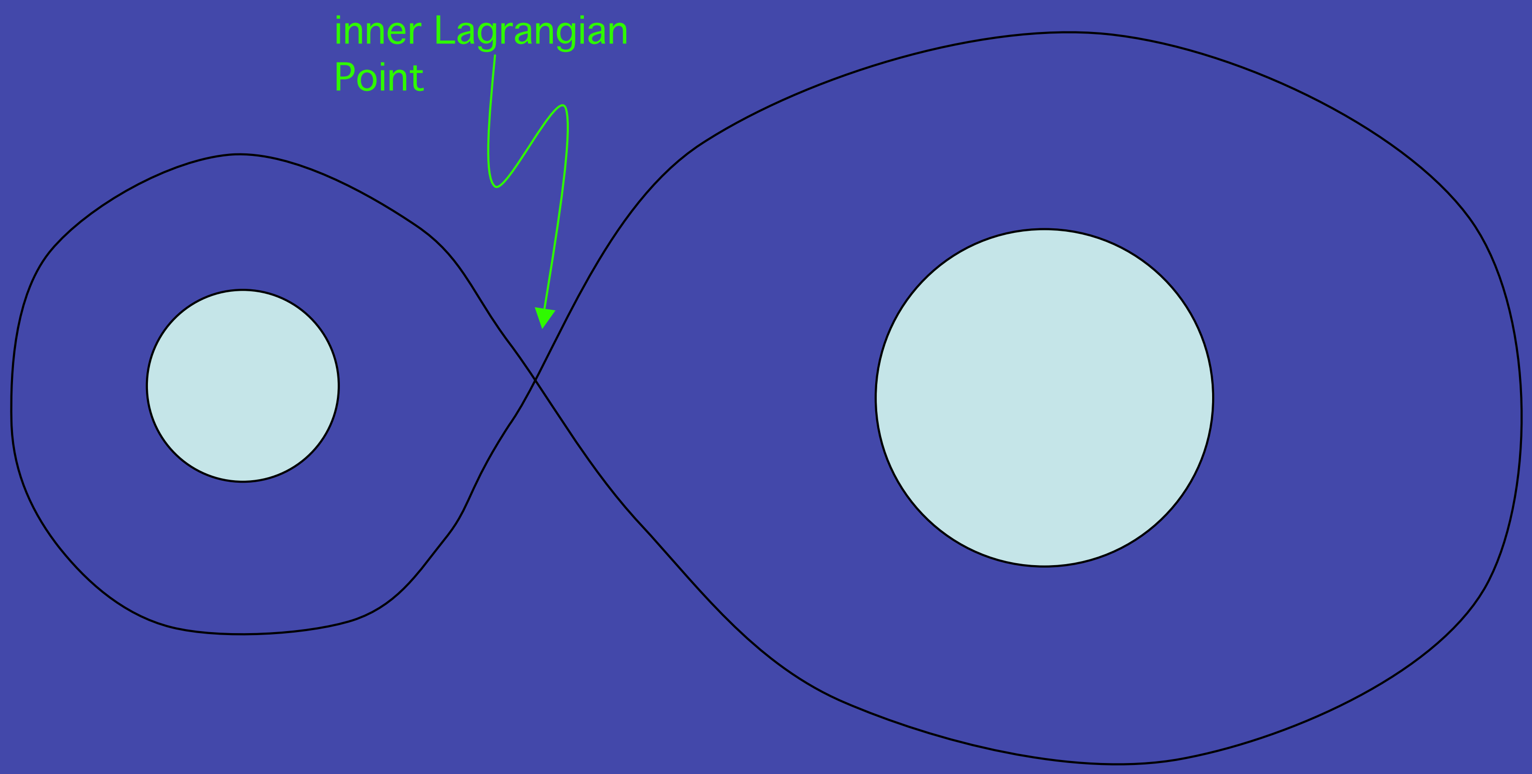
$$L_E = 4\pi G M m_p c / \sigma_T = 1.2 \times 10^{38} \left(\frac{M}{M_\odot}\right) \text{ ergs s}^{-1}$$

Binary Star Evolution

Stars in binary systems evolve individually and together

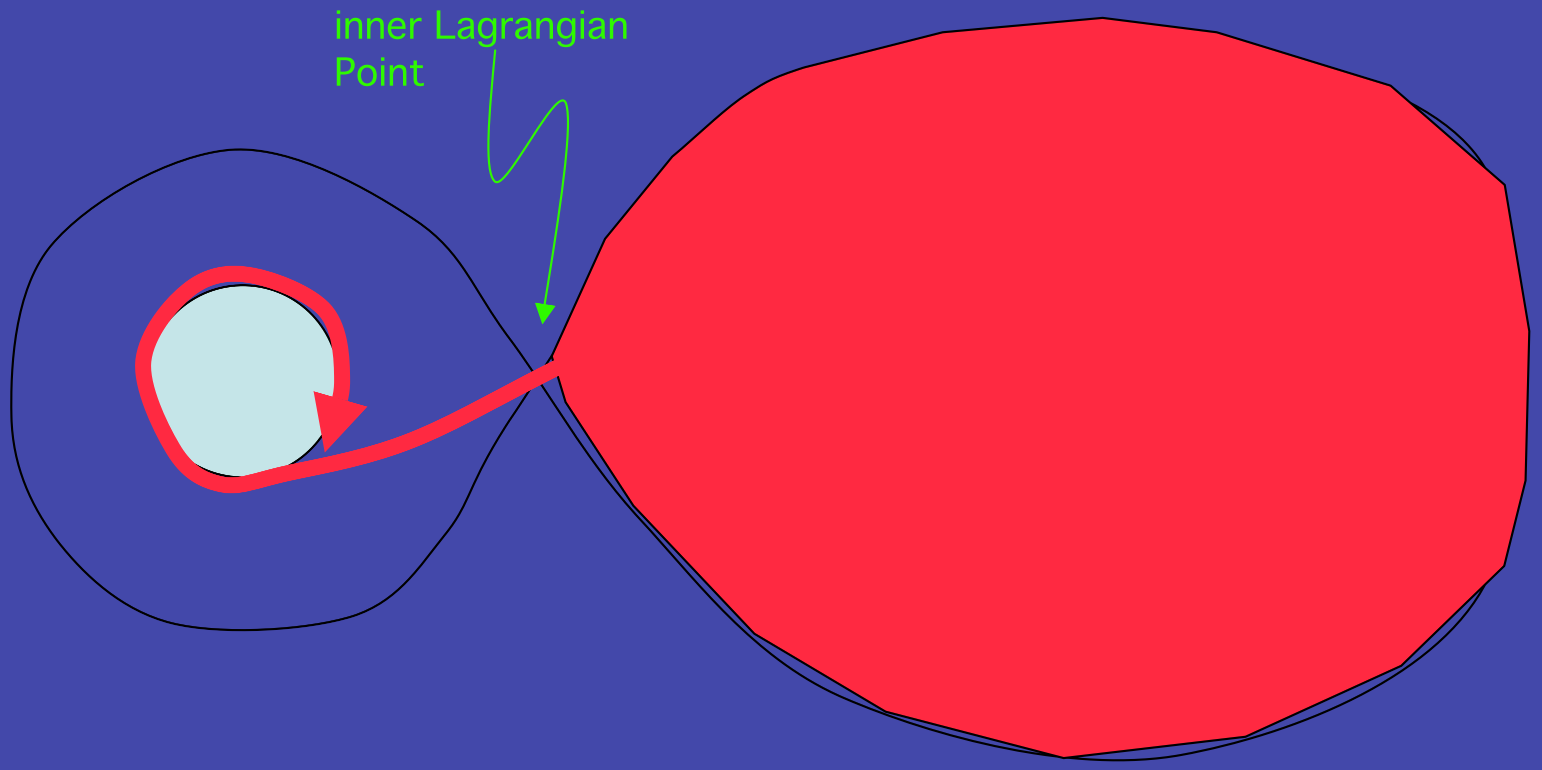
- individually: evolution follows normal progression based on mass
- together: stars can interact, exchange mass, angular momentum...

Equipotentials



Along the equipotential, the gravitational + centrifugal potentials = constant

Evolution along an Equipotential



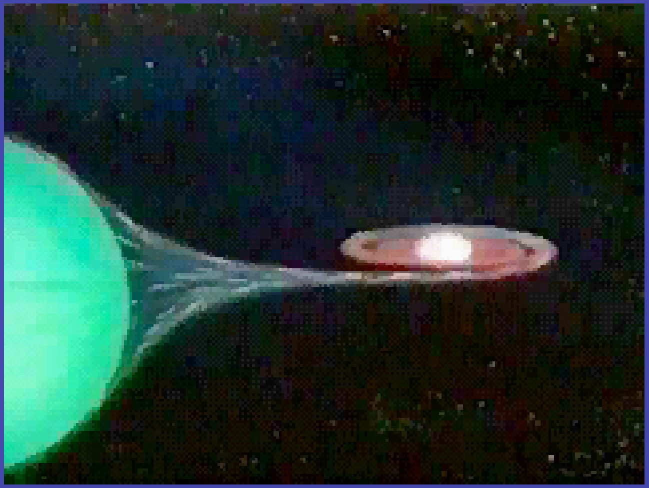
As more massive star moves towards the Red Giant Phase, it encounters the critical Roche equipotential and mass is transferred from the primary to the secondary through the ILP

Interactions

Mass transfer can either be

- conservative: mass lost by primary is gained by the secondary
- non-conservative: mass lost by the primary is lost to the system
- or some combination

Stars in binaries can exchange angular momentum
Also interact via tidal force



Algols

Mass ratios are a function of time.

Mass exchange can make the originally lower mass star more massive than the (originally) higher mass star

Algol Paradox: Algol (β Per), B8 dwarf + K giant; giant star more evolved but less massive, due to mass transfer from giant (originally more massive) to B8 star (originally less massive)

Conclusions

Star formation driven by gravity vs. kinetic energy, spin, magnetic field: disks and jets important

Angular momentum can be stored in a stellar companion, or in a stellar disk

Evolution of a star driven by mass

Low mass and high mass stars evolve differently

Single and binary stars evolve differently

Eventually stars die